In-line regeneration of RZ-DPSK signals using four-wave mixing in a fiber

Masayuki Matsumoto
Osaka University, Department of Communications Engineering, 2-1 Yamada-oka, Suita, Osaka 565-0871, Japan
Tel: +81-6-6879-7729, Fax: +81-6-6879-7774, Email: matumoto@comm.eng.osaka-u.ac.jp

Abstract: In-line signal regeneration using FWM in a fiber, which stabilizes amplitude while maintaining phase information carried by the signal, is analyzed. It is shown that RZ-DPSK quasi-linear transmission performance can be improved by the regenerator.

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1. Introduction

Fiber-based all-optical signal regenerators have a potential of ultra-high speed operation and will play an important role in future high-speed photonic networks. Various kinds of nonlinear phenomena including self-phase modulation, cross-phase modulation, and four-wave mixing have been utilized for the realization of regenerator functions such as noise suppression and signal-level stabilization. Most of the regenerators reported so far have been designed to regenerate on-off-keyed signals. Recently it has been demonstrated that phase-manipulated modulation formats such as return-to-zero differential-phase shift keying (RZ-DPSK) and carrier-suppressed RZ (CS-RZ) show better performance in long-distance WDM transmission [1,2]. Signal regenerators or regulators that can maintain phase information imposed on the signal, therefore, will be desired [3]. In this paper, performance of an all-optical in-line signal regenerator utilizing four-wave mixing in a fiber, which maintains phase information during amplitude regeneration, is numerically studied.

2. Regenerator based on FWM in a fiber

The regenerator consists of a saturable absorber (SA), a CW pump source, a highly nonlinear fiber (HNLF), and an optical bandpass filter (OBPF) as shown in Fig.1. The signal fed into the HNLF experiences FWM interaction and is extracted by the OBPF without wavelength conversion [4]. The amplitude stabilization comes from the ultra-fast saturation of the FWM interaction. The insertion of SA allows stabilization of zero state, and therefore, stable propagation of RZ pulses. SA is not needed if one uses higher-order FWM interaction [5,6]. In this case, however, care has to be taken for the choice of FWM order because (1) the use of FWM product whose amplitude is proportional to even power of the signal amplitude can not maintain binary phase information (0 or π) and (2) larger phase fluctuation will be induced by the use of higher FWM orders. Data-pumped parametric amplification can also be used for 2R regeneration without SA [7]. This, however, does not preserve phase information on data signals. Furthermore, the output wavelength necessarily differs from the input signal wavelength in these cases, which needs multiple FWM stages in each regenerator for wavelength-conversion free operation.

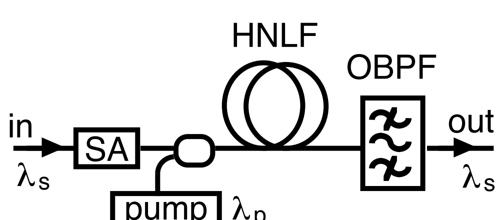

Fig.1. Schematic of a signal regenerator. SA: saturable absorber, HNLF: highly nonlinear fiber, OBPF: optical bandpass filter.

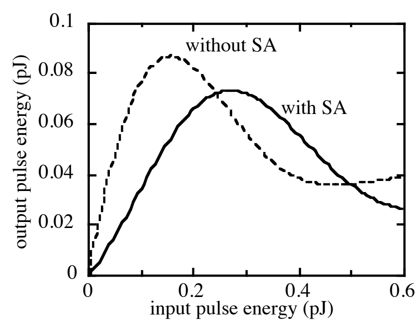

Fig.2. Energy transfer function of the FWM regenerator with and without saturable absorber.

3. Single-pulse transmission

Fig.2 shows an example of energy transfer function of the regenerator (with or without SA), where a chirp-free Gaussian pulse with fwhm of 7.2 ps is launched. HNLF length, loss, nonlinearity, and dispersion slope are 1.5km, 0.5dB/km, 16.2/W/km, and 0.03ps/nm^2/km, respectively. λ_p-λ_s = λ_s-λ_0 = 3nm (λ_p, λ_s, and λ_0 are pump, signal, and zero-dispersion wavelengths, respectively), pump power is 30mW, and bandwidth of the OBPF (Gaussian) is 150GHz. Because of saturation of the first-order FWM interaction and generation of higher-order FWM components, the transfer functions exhibit peaks at input energies of 0.15pJ and 0.27pJ for the regenerators with and without SA, respectively. The SA is assumed to have a power transmission coefficient $T(t)= [T_0+P_{in}(t)/P_s]/[1+P_{in}(t)/P_s]$, where T_0, $P_{in}(t)$, and P_s are unsaturated transmissivity, input signal power, and saturation power, respectively [8]. We neglect here the transient of SA in order to simplify the analysis. This is allowed for artificial SAs based on ultrafast fiber nonlinearity [9]. For SAs made by semiconductors, their transient dynamics should be considered for precise characterization at high-speed operation [10]. T_0 and P_s are 0.2 and 40mW, respectively, in the numerical simulation in this paper. Fig.2 shows that the insertion of SA reduces the transmission ratio at small input energies, which is needed for the suppression of zero-state instability.

Fig.3(a) shows the energy of a single pulse traveling over directly-cascaded regenerators starting with different initial amplitudes. Initial pulse width is fixed at 7.2ps. When amplification with proper amount of gain G is provided between regenerators, stable transmission of RZ pulse can be obtained. (G=3.2 in Fig.3.) Pulses having initial amplitudes smaller than a threshold (~ 0.07pJ) decay as N increases, which shows the 2R behavior of the regenerator. Fig. 3(b) shows corresponding evolution of phase at the pulse peak. Phase deviation from the stationary pulse is plotted in the figure. Fig.3(b) shows that phase shifts are induced to the pulse in the course of stabilization of its amplitude by the use of fiber nonlinearity. This will limit the effectiveness of the regenerator in DPSK systems as will be shown in the next section.

4. Improvement of RZ-DPSK signal transmission by means of the in-line regenerator

The effect of the regenerator in single-channel 40Gb/s quasi-linear RZ-DPSK transmission is then studied. Each amplifier span (80km) of the system consists of a pair of standard single-mode fiber (40km, D=17ps/nm/km, α= 0.22dB/km, and γ=1.3/W/km) and reverse dispersion fiber (40km, D= -17ps/nm/km, α=0.27dB/km, and γ=4.46 /W/km). The in-line amplifiers have NF of 4dB. Average signal power launched into the fiber is 1mW. Signal quality is numerically evaluated in terms of Q factor and eye-opening (EO) degradation calculated from eye patterns obtained after a delayed interferometer, balanced detection, and low pass filtering. The EO degradation (dB) is defined by $-10\log[E_R P_T/(E_T P_R)]$, where $E_{R(T)}$ is the eye opening at the receiver (transmitter) and $P_{R(T)}$ is the average signal power at the receiver (transmitter).

Fig.4 shows Q factor and EO degradation versus distance when no regenerators are inserted (dashed curve), regenerators are inserted every 6 spans (solid curve), and regenerators are inserted every 3 spans (dotted curve). Fig.4 shows that the phase information on the signal is not destroyed by the FWM regenerators and that the regenerators can improve transmission performance. It is also shown that at distances longer than ~2000km the quality of the signal regenerated every 3 spans becomes worse than that of the signal regenerated every 6 spans. This is because the accumulation of phase fluctuation induced by the amplitude regeneration as noted above is more significant for the case of more frequent regeneration. Fig.5 shows distribution of pulse amplitude and phase at pulse

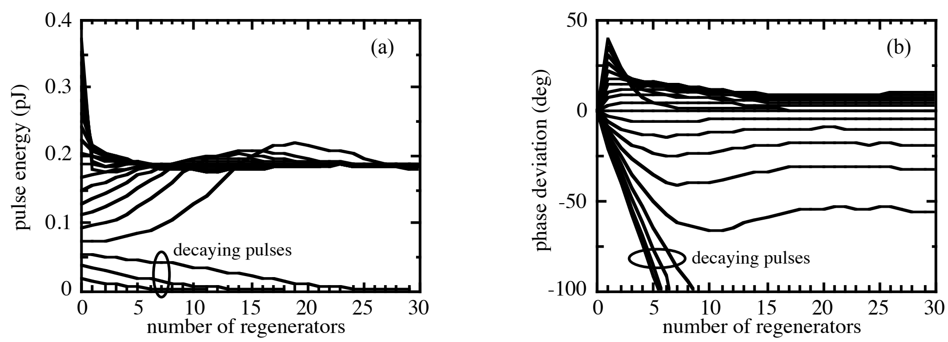

Fig.3. Evolution of pulse energy (a) and phase at pulse peak (b) in cascaded regenerators. Initial pulse amplitude is varied among 20 different values. Gain of the amplifier between regenerators is fixed at 3.2.

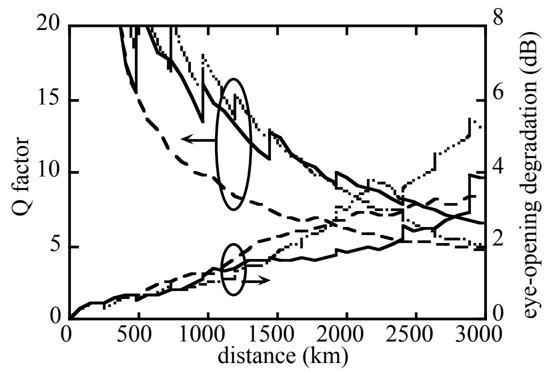

Fig.4. Q factor and EO-degradation versus distance for 40Gb/s quasi-linear transmission.

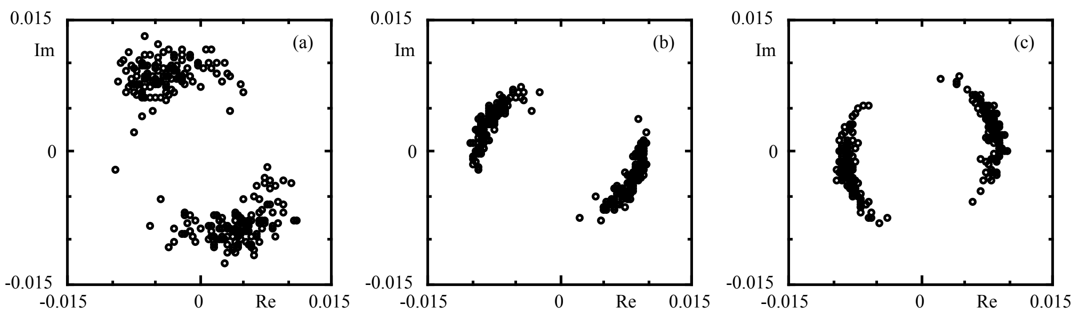

Fig.5. Distribution of amplitude and phase at pulse peaks at 2960km. (a) No regenerators are inserted, (b) regenerators are inserted every 6 spans, and (c) regenerators are inserted every 3 spans.

peaks of 256 pulses used in the simulation at a distance of 2960km. It is shown that the regenerators strongly stabilize pulse amplitude. It is also shown that the phase fluctuation is slightly larger when the regenerators are inserted every 3 spans than the case of insertion at every 6 spans.

5. Conclusion

Performance of an all-optical in-line signal regenerator utilizing four-wave mixing in a fiber was numerically studied. It was shown that stable RZ pulse transmission can be achieved with its phase information almost maintained. Unnecessarily frequent regeneration, however, will cause accumulation of phase fluctuation, which degrades transmission performance.

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